Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 2 (2024)

Designing Efficient and High-Performance Induction Motor for future Electric Vehicles Optimization Strategies

B. Devi[1*], V. Sureshkumar[2]
[1,2] Department of EEE, Thiagarajar College of Engineering, Madurai, Tamil Nadu, India.
[*]Corresponding author: B. Devi

Abstract

This work investigates the optimum design of a 3Φ Squirrel-Cage Induction Motor (3Φ-SCIM) for future Electric Vehicles (EVs) propulsion utilizing the Hook-Jeeves (HJ) optimization method. Various design parameters including pole count, rated and maximum speed, groove count, and configurations of stator/rotor slots are thoroughly analyzed. This work evaluates optimal designs for both two-pole and four-pole motors, focusing on efficiency as a key performance metric. The results suggest that a motor with a 2-pole shape in rectangular designed slots of stator and rotor, operating at a designated rotating speed of 1800 rpm, displays very high efficiency, positioning it as the optimal choice for EV applications. This work contributes to the understanding of 3Φ SCIM optimization for electric vehicles, offering insights for enhancing motor performance in such contexts.

Keywords: *Squirrel-Cage Induction Motor (SCIM), Electric Vehicles (EVs),Optimization, Hook-Jeeves algorithm.*

I. Introduction

EVs provide a solution to urban pollution and noise by tapping into electric energy distribution[1]. Despite challenges like low power density and long charging times, optimizing motor design and battery technology, along with efficient energy management, can enhance EV performance. Expanding charging infrastructure is key to widespread adoption, offering a sustainable alternative to traditional vehicles in cities. The concept of EVs traces back to the early 20th century, around 1916 [2]. However, it fell into unimportant due to the abundance of fossil fuels, limited awareness of smog air pollution, and constraints on resources in electrical energy field. It wasn't until around 1980, amid a fossil energy crisis marked by dwindling resources and soaring fuel prices, along with growing concerns about respiratory and noise air pollution, that concentration returned to EVs. This resurgence led to the design of various EVs featuring different Electric Motors (EMs) [3-8].

DC motors are appreciated for their straightforward control systems but suffer from issues with commutators and brushes, leading to maintenance concerns. Switched Reluctance Motors (SRMs) offer simple construction but are plagued by high noise levels, necessitating complex control algorithms. The shortcomings of these motors have prompted a shift towards AC motors, particularly Induction Motors (IM s), which boast simple designs, low cost, and high energy density. IMs have surged in popularity due to their reliability and affordability, offering a compelling option for various industrial applications.

EV motors must meet key requirements for optimal performance, including high inertia-to-torque and weight-to-power ratios, substantial braking torque, high speed, low noise, minimal maintenance, compact size, and simple control [9-16]. They should also offer cost-effectiveness, high efficiency across various speeds, and the capability to regenerate energy during braking or downward- sloping hill movement. Among EV motor types, the SCIM stands out for fulfilling these criteria efficiently, making it a preferred choice for electric vehicles.

Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 45 No. 2 (2024)

Table. 1. Comparison of optimum designed induction motors using various methods

Parameter	Methods				
	Daviden-Fletcher-Pavel	Deepest slope	Hook-Jewes	Pavel	Random search
BrakingTorque (Pu)	2.9	3.04	3.14	3.06	3.34
Initial Torque (Pu)	2.53	2.87	1.98	2.92	2.25
Initial current (A)	48.62	51.84	53	50.78	53.4
Slip (%)	4.27	4.47	4.64	4.67	4.84
Power factor	0.891	0.87	0.872	0.86	0.856
Cost ($)	293.54	331.07	263.9	265.59	325.98
Optimization time(s)	52	101	16	51	36
Temperature(℃)	72.54	64.38	74.07	74.97	63.4
Number of repetitions	31	12	4	5	10

Various optimization techniques have been employed to design induction motors efficiently. These methods include Hook-Jewes (HJ), Deepest Slope (DS), Random Search (RS), Pavel (P), Simple (S), Daviden-Fletcher-Pavel (DFP) method, direct search, Niching Genetic Algorithm according to the Rosenberg method, Monica (M), First-Order Gradient (FOG), and finally Neural Network (NN) based on optimization .

Table I presents the results Comparision achieved using distinct five optimization approaches concerning the objective function, which focuses on the cost of consumables. This comparison pertains to a 7.5 kW IM with 4 poles, as detailed in references[17] and [18]. The detailed comparitive analysis presented in the above table no I indicates that HJ method demonstrates superior achievement. Taking this into account, along with recommendations from several authors cited in references [19] to [27] and , the HJ have been selected for the excellent optimal design of the EV's Induction Motor (IM).

Apart from the impact of dimensional parameters on EV motor performance, the rated values and constant parameters of the motor also play a crucial role. These factors encompass rated power, speed,voltage, torque, peak speed and slot configuration and pole count. The power, maximum speed, and torque are calculated based upon anticipated EV performance. Voltage selection hinges on existing infrastructure, with higher voltages typically offering better efficiency, although constraints such as battery voltage may limit this choice.

Slot count is determined by design standards, while a more detailed analysis is needed for rated speed, pole count, and slot configuration. By comprehending the influence of these parameters on EV system performance, an appropriate mixing of nominal values and features are chosen for beginning design value, ultimately leading to final optimal design.

This work examines and evaluates the impact of the total poles, rated speed, and groove shape on the efficiency of a 3-phase EV Induction Motor (IM). It optimally designs a 15-horse power three-phase IM for EVs by varying these features and ultimately presents the final optimal design.

This work comprises exclusively six sections. The section two explores the consequences of the no of poles, nominal speed, and shape of groove on motor overall efficiency. In the section third, the method for determine the engine efficiency is outlined. The fourth part fall into the optimal design of the motor and fifth part discuss about design of sample motor. Finally, conclusions are drawn in the last section.

II. Investigating the Impact of Pole Count, Groove type, and Nominal Speed on Motor Efficiency

The Electric Vehicle's Induction Motor (EV's IM) needs to operate across a broad scale of speeds, from zero to many one thousand revolutions per minute. It must also fulfill various EV requirements, such as delivering sufficient torque for acceleration and maintaining constant speeds, while exhibiting a small mechanical time constant for dynamic and rapid responses. Efficient utilization of battery energy is essential, necessitating high motor efficiency and a design that minimizes torque fluctuations caused by power source harmonics and noise generation. To achieve fast dynamics, the motor system should be lightweight and occupy minimal space. Consequently, the design of the EV's IM differs from standard IM designs typically used in industry. The Voltage Source Inverter (VSI) gives maximum leakage inductance to minimize keying frequency and associated losses. Deep grooves in the motor should be avoided to reduce skin effect losses and associated costs, as well as to prevent instability at different motor speeds.

Since the motor with an inverter power supply doesn't face starting torque issues, deep grooves on the rotor aren't necessary to enhance acceleration. A larger groove space is required for specific power and conductor thickness, given the limited power supply voltage range from the battery. Considering the high motor speed, the rotor diameter should be small, resulting in fewer grooves on the pole. As a result, the no of motor poles is typically selected between two and four to meet these design criteria effectively.

In high-frequency motors like those used in EVs, reducing skin effect and associated losses can be achieved by selecting the appropriate shape for the rotor groove. Typically, in high-speed IMs such as EVs, rectangular-shaped rotor grooves are preferred, where the length and width are closely matched. Moreover, increasing voltage helps to distribute flux more effectively across various groove parts , thereby reducing harmonic losses.

The ultimate motor speed rely on factors like the selected transmission method and the vehicle peak speed. However, when selecting the base and nominal speed (where the base speed equals the nominal speed), factors such as pole count, groove type, losses, and operating conditions are also considered. Choosing the nominal speed in alignment with the machine's operating frequency at that speed directly impacts keying losses and harmonics. Additionally, it affects the motor's moment of inertia. Therefore, selecting the optimal nominal speed simultaneously addresses the motor transients and finally benefits the EV's performance.

III. Analyzing Efficiency Metrics: Calculations and Insights

When the induction motor is energies by use an inverter, it creates extra losses compared to regular powering with a smooth sine wave. These losses come from things like increased magnetic field changes, more resistance in the motor's wires, and other factors like friction. These losses make the motor less efficient. So, when designing or using these systems, it's important to consider and minimize these losses to make the motor work better.

A. Core losses

By using equation 1 the induction motor total core losses can be calculated:

$$P_C = \sum_m P_{cm} = \sum_m (P_{hm} + P_{em}) \qquad (1)$$

Eddy current and Hysteresis losses of harmonics are determined using equation (2) and (3) for overall weight of several components of the motor magnetic circuit (core) :

In accordance to the provided equation, the harmonic losses are computed individually for every part of the motor by multiplying the weight of the respective component.

$$P_{hm} = \sum_i P_{hmi} = \sum_i G_i P_{hmi} = \sum_i G_i K_h \sigma_h f_m B^k_{mmi} \qquad (2)$$

$$P_{em} = \sum_i P_{emi} = \sum_i G_i P_{emi} = \sum_i G_i K_e t^2 f^2_m B^2_{mm1} K_{\frac{Em}{pi}} \qquad (3)$$

B. Resistor losses for rotor and stator

The overall losses, encompassing both rotor and stator, to be determined using equation (4) by summing up the losses associated with the different current harmonics.

This relationship is expressed as follows:

$$P_\Omega = \sum_m i_3 \left(R_{SM} I^2_{sm} + R_{rm} I^2_{rm}\right) \qquad (4)$$

C. Mechanical losses

Using the provided relationship, it is possible to calculate these losses at various speeds:

$$P_n = 8 D_r (L + 0.15) V_a^2 \qquad (5)$$

Finally efficiency and over all losses are

$$P_{loss} = P_{\Omega} + P_C + P_{fw} + (P_p + P_z + P_k + P_{bu}) \quad (6)$$

$$P_{in} = \sum_m 3V_m I_{sm} cos\emptyset_m \quad (7)$$

$$\eta = \frac{(P_{in} - P_{loss})}{P_{in}} \quad (8)$$

D. Rated and failure torques at rated and peak speeds

The below equation gives the torque values :

$$T_n = \frac{\sum_m 1.5PR_{rm}I_{rm}^2}{m\, f_m S_m} \quad (9)$$

$$T_{Pb} = \frac{1.5E_{S1}}{(X_{r1}W_S)} = \frac{T_n R_{r1}}{X_{r1}} \quad (10)$$

$$T_{Pm} = \left(\frac{f_b}{f_{max}}\right)^2 \quad (11)$$

E. Inertia coefficient

The following formula is used to calculate coefficient, that controls the motor's negative and positive accelerations.

$$H = 0.5W^{2\frac{\sigma^2}{Q}} \quad (12)$$

IV. Optimum design of motor

A number of techniques that are employed for the best design of EV's IM have been examined for the optimal design. Only the IM's objective functions, constraints, and optimization variables are covered in this section.Diverse perspectives exist on the ideal motor design, which includes: lowest possible cost, highest possible efficiency, least amount of space or weight, best performance (like minimum slippage, maximum power factor, etc.), as well as a multidimensional perspective. Efficiency is extremely vital in an EV because of the energy and battery power limitations that should be used.

Additionally, a lightweight motor is necessary to lower the overall weight of the vehicle and, consequently, the energy consumption. Thus, weight and efficiency are the two main factors to consider when designing an ideal EV. One can select the objective function.

Obviously, it is possible to create a design using various mixing of these viewpoints, and the greatest combination that yields the most appropriate desired result is the ideal design. Only the efficiency function has been covered in this article because the primary objective is to differentiate the effects of selecting the pole numbers, the kind of groove, and the rated speed on the transient and stable motor performance.

Other objectives, referred to as secondary goals, are also sought in the design optimization process. These objectives include enhancing or preserving the motor's intended performance. Since expanding the goal function—a multidimensional function with several, varied components—limits the search space for the optimized software and slows down the optimization process, it is unlikely that good results will be found. As a result, these secondary objectives are applied as limitations to the optimization process rather than being directly incorporated in the objective function.

The following are the most significant limitations that were taken into account for this work: the maximum temperature increase of 75 °C, the less production torque, the less breakdown torque at maximum speed of 3.5 Nm, the small ratio of torque failure to nominal speed of 1.5at rated torque , the maximum rotor speed of 120 m/s, the maximum time constant of rotor is 4 s,the stator's tooth maximum flux density of (1.2 Tesla), the highest total cost (if necessary), and the maximum volume or weight .

IM has a large number of design factors. Generally speaking, more optimization variables lead to better results in optimization, but the convergencerate is much slower and the optimization process is more challenging to manage. As a result, make every effort to limit the no of parameters and to employ parameters that have a bigger impact on the ideal design as the initial optimization parameters. Based upon this, the following factors are discussed in this work: the stator's inner diameter, the core's length, the stator and rotor groove's width and depth, the depth of the rotor and stator rings, the air gap's length, and thecross-sectional surface of the stator.

Apart from the aforementioned elements, one moreparameter also take into account the operating voltage, rated and higher speeds, the quantity and kind of rotor and stator grooves, and the number of poles. Because of the battery potential limitation and other constraints, the operating voltage of the motor in this work has been set at 96 V. The motor's maximum speed has been chosen in accordance with the maximum speed that the 900 rpm. For a 2-pole motor, the slots number in the stator and rotor after the optimization is changed and repeated is 18 and 13, and for a 4-pole motor, it is 24 and 18. The three main topics covered in this work are the rated speed, the kind of grooves, and the number of poles. Various optimal designs with various rated speed,groove type, and no of pole values are analyzed and their efficiencies are compared. Lastly, the best design is shown based on the comparisons.

V. Design of the test motor

This section designs a SCIM for EVs and examines and analyzes the impact of selecting the no of pole counts, the kind of rotor and stator slots, and the rated speed on the performance of motor's parameters. The first five harmonics of the supply voltage—the fifth, seventh, eleventh, thirteenth, and seventeenth harmonics—are considered in the design with corresponding values of 0.973, 0.089, 0.018, 0.016, and 0.052. The motor has a nominal power of 15 horsepower and the highest speed of 900 revolutions per minute.As stated by the comparisons in part II, there will only be two or four options for the amount of poles. Two varieties of circular and rectangular grooves are examined in the limit state in order to compare the effects of the grooves. The rated speed range is set between 1600 and 2000 rpm since raising the nominal speed causes the system's efficiency to decline.

In the 2-pole configuration, the stator and rotor have 18 and 13 slots, respectively; in the 4-pole design, there are 18 and 4 extra slots to pick from. The outcomes of several ideal designs for rotor and stator grooves in rectangular shape, round rotor grooves, and rectangular stator grooves are displayed in Tables 2 and 3, respectively. For rectangular stator and rotor grooves, it has been noted that:

1. For three nominal speeds, the two-pole motor's volume is much smaller than the four-pole motor's (43% on average).
2. The four-pole motor has a bigger volume, but it weighs less because of its rectangular shape and round rotor groove.
3. The two-pole motor's rotor moment of inertia is substantially lower compare to the four-pole motor's (average of 49%).
4. The two-pole motor has a 0.95 percent better efficiency than the four-pole motor. The two-pole motor has an average power factor that is 17% greater than the 4-pole motor's, and the two-pole motor meets the power factor requirements while the 4-pole motor does not.
5. The two-pole motor can handle maximum overload at its maximum level speed since its braking torque is stronger (2.85% on average) at that speed.
6. The two-pole motor has the capacity to handle greater additional load and more dynamic acceleration at the nominal speed due to its average 3.04 percent higher braking torque.
7. For all 2-pole designs, the temperature increase has been computed; however, for four-pole designs, the calculation has only been done for the rated speed of 1600 rpm.
8. 2-pole designs cost more (14.35 percent on average).

Designs with round rotor grooves and rectangular stator grooves yield results that are almost identical (Table III). Generally,this can be said that design configuration with rectangular rotor and stator grooves perform much better than those with round rotor and rectangular stator grooves.

Table II. Optimum results for rectangular shaped stator and rotor grooves

No of Poles (P)	2			4		
Rated Speed(rpm)	1500	1800	2200	1500	1800	2200
L(m)	0.0847	0.0853	0.0782	0.1397	0.1325	0.1302
D0(m)	0.3244	0.3202	0.3240	0.3158	0.3075	0.3051
D(m)	0.1287	0.1265	0.1292	0.1397	0.1325	0.1302
W(kg)	40.67	39.68	38.66	37.79	33.74	32.44

V(m^3)	0.0032	0.0031	0.0032	0.0052	0.0046	0.0044
C($)	124.0	121.2	118.3	113.9	103.3	97.7
J(kgm^2)	0.0286	0.0264	0.0273	0.0476	0.0368	0.0337
η(%)	87.00	86.85	86.50	86.47	85.99	85.43
Pf(w)	0.864	0.861	0.855	0.742	0.736	0.727
T(°C)	63.96	61.82	66.21	61.81	67.07	67.84
T_{pm}(Nm)	4.494	4.758	5.041	4.334	5.676	4.961
T_{pb}(Nm)	110.56	93.95	81.84	105.51	91.92	80.22
W_s(m)	0.0222	0.0222	0.0222	0.0222	0.0222	0.0222
d_s(m)	0.0266	0.0266	0.0266	0.0262	0.0262	0.0262
W_r(m)	0.0148	0.0145	0.0145	0.0126	0.0125	0.0123
d_r(m)	0.0237	0.0235	0.0245	0.0182	0.0156	0.0150

Table III. Optimum design results for rectangular stator and round rotor grooves with a rated speed of 1800 rpm

P	2	4	P	2	4	P	2	4
L(m)	0.1000	0.0845	D_0(m)	0.3622	0.2282	D(m)	0.1263	0.1397
W(kg)	43.05	29.49	V(m^3)	0.0037	0.0034	C_t($)	131.4	89.1
J(kgm^2)	0.0293	0.0307	η(%)	86	84.25	Pf	0.852	0.742
T(°C)	73.82	79.52	T_{pm}(Nm)	4.148	3.611	T_{pb}(Nm)	103.71	90.31
W_s(m)	0.0112	0.0091	d_s(m)	0.0266	0.0332	W_r=d_r (m)	0/0174	0.0148

Table II values has been plotted which is based on the rated speed. The curves for the stator inner diameter changes in the following order are shown in Figures 1A through 1E: moment of inertia, volume,maximum breaking torque and rated speeds, power factor and efficiency with the changeover in speed range from 1500 rpm to 2700 rpm for two-pole designs. For both two-pole and four-pole designs,an raise in the average rated speed results in a lower in the stator's inner diameter,core length,cost,moment of inertia,power factor and efficiency. The breaking torque at the nominal speed is affected in the opposite way. it is possible to argue that decreasing the nominal speed leads to better design, or raising the nominal speed causes worse design, given that efficiency optimization is the goal function.

The following factors are crucial when choosing motors for electric vehicles since they increase the nominal speed while taking into account the volume, weight, moment of inertia, and intended price. Therefore, in order to ensure that both primaryand secondary goals are as closely as possible accomplished, an alternative should be chosen in accordance with the aforementioned needs and the planned categorization in the case of the motor engine.The motor's optimal design solely considers the motor's losses; switching losses are ignored.

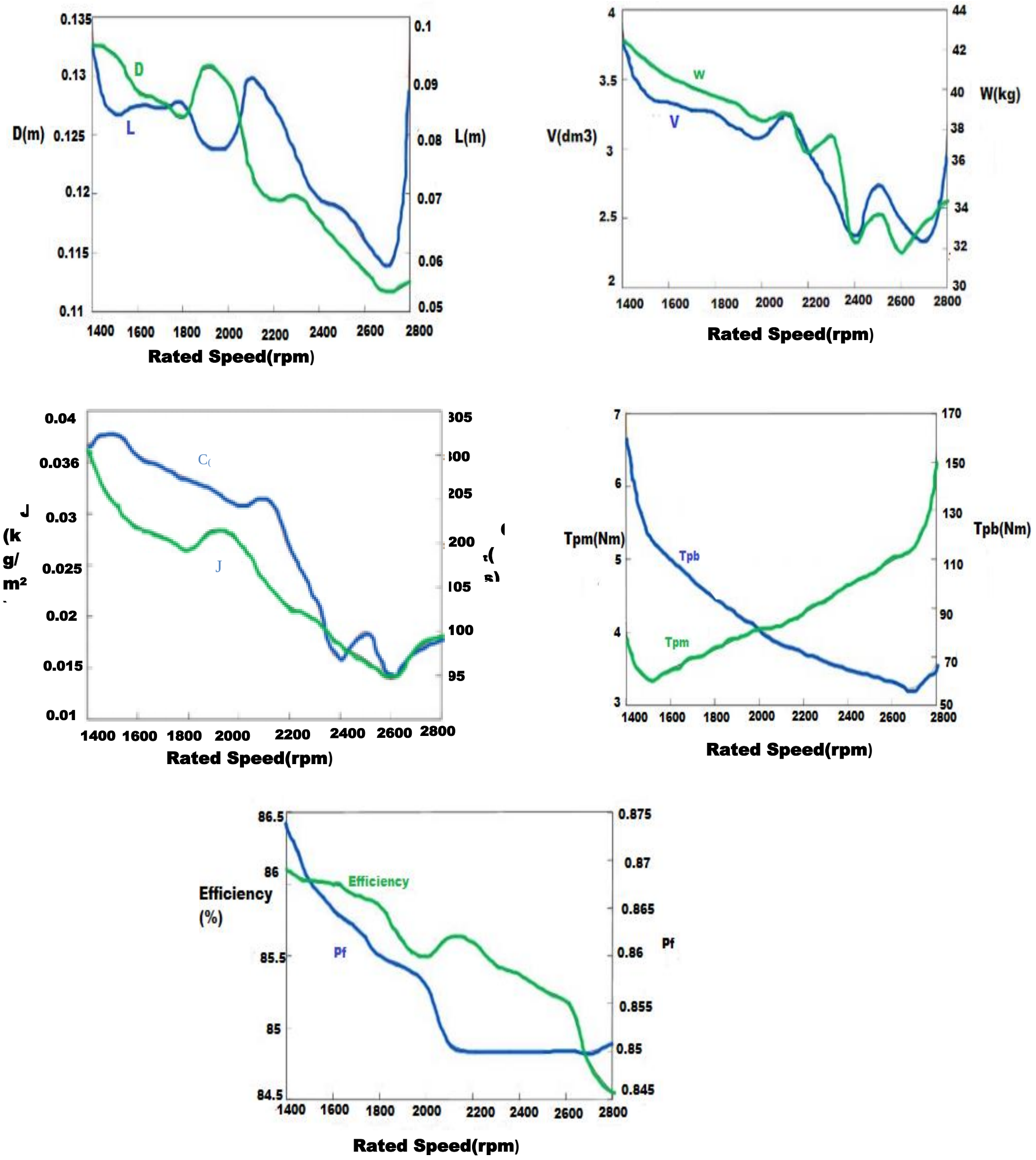

Fig. 2. characteristics curve for various parameters of two-pole motor

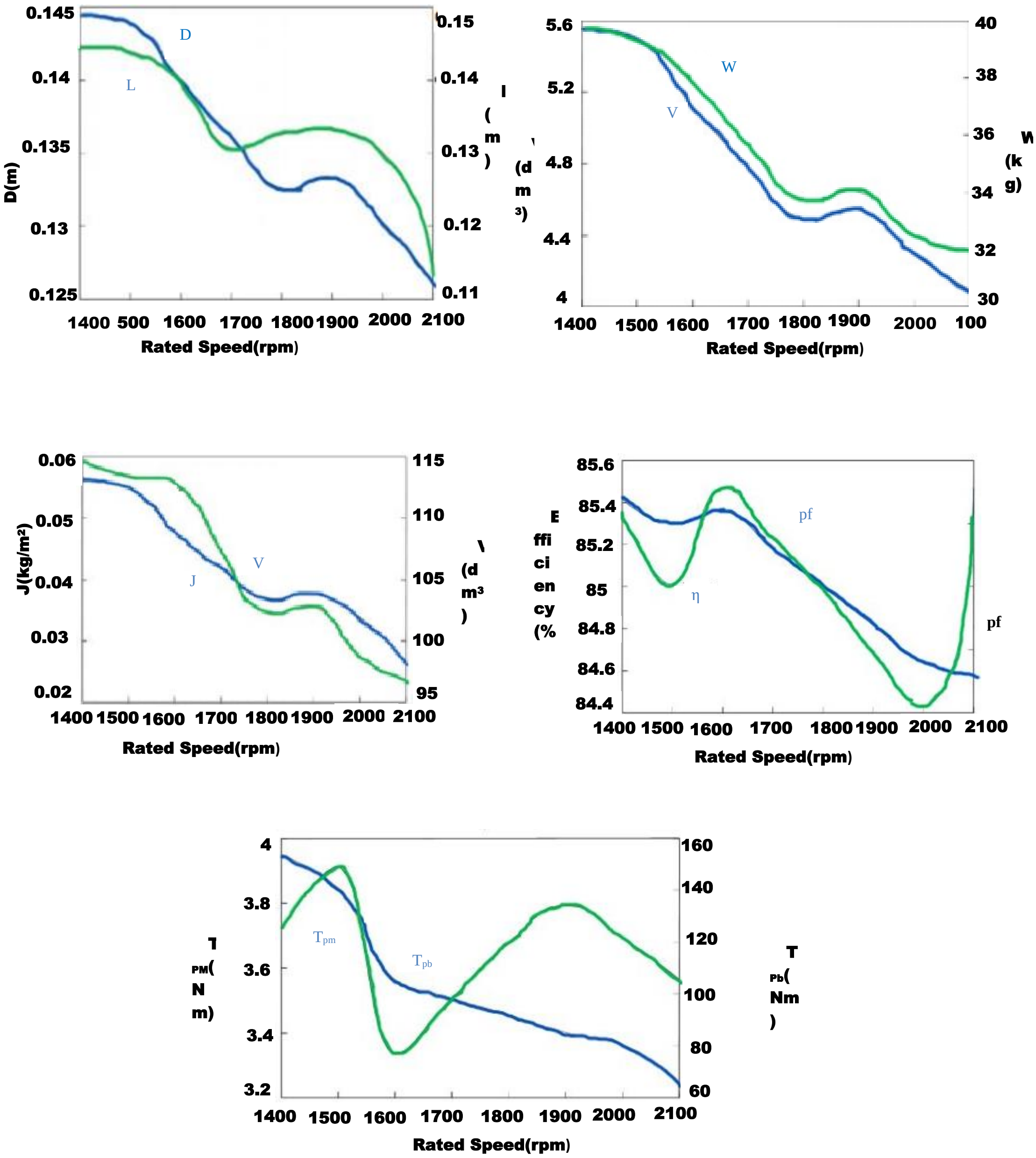

Fig. 3. characteristics curve for various parameters of four-pole motor design

VI. Conclusion

The following outcomes can be obtained by looking at and evaluating several plans with various configurations:

1. Optimal design outcomes are desired even when a less supply voltage is selected (to restrict the battery voltage) and the fifth harmonics in the voltage waveform are seized into consideration.
2. When compared to a four-pole motor, the two-pole motor's drawbacks are its high cost and weight.
3. Better motor efficiency is achieved using rectangular shaped grooves for the rotor and stator in two-pole configurations as opposed to circular grooves for the rotor. In four-pole designs,theaforementioned is not true.
4. For two- and four-pole designs, raising the rated speed during the design stage affects the breakdown torque at rated speed,power factor, efficiency, cost, weight,volumeand moment of inertia; conversely, the breakdown torque increases at maximum speed. These results implies that raising the rated speed results in an unsatisfactory plan when taking into account the goal function (yield). However, raising the rated speed is necessary to meet the

secondary objectives (volume,moment of inertia and weight). An additional component that restricts the rated speed.

Based on the continuous operating mode results, the two-pole motor with a rated speed of 1800 rpm is the optimal design for an electric vehicle.

Nomenclature

P_{hm},P_{em} -hysteresis and core losses to m-th harmonic and total core losses
K_h,K_e -Coefficients of hysteresis and eddy losses
S_m, f_m- shift and frequency to the m-th harmonic
B_m -maximum magnetic flux density(Tesla)
t,r- thickness of steel sheets in millimeters and specific resistance in ohms per centimeter
R_{sm},R_{rm}-rotor and stator resistance
I_{rm},I_{sm} -rotor and stator current
V_{sm},cosΦm-voltage and power factor
V_a-linear speed of the rotor in m/s
D_s,D_r -depth and width of rotor and stator grooves
P_h-losses due to the flow of leakage of teeth in watts
P_z-losses due to the flow of zigzag leakage in watts
T_{pb},T_{pm}- Maximum and nominal torque
Pf,η-Power factor and efficiency
H,J,T-inertia constant,moment of inertia, temperature

Acknowledgement

This work was funded under the Thiagarajar Research Fellowship Scheme (File no: TRF/JAN-2022/05). Also, the authors would like to Thanks the Department of EEE, Thiagarajar College of Engineering, Madurai for furnishing the facilities to perform this work.

Conflicts of Interest:No conflict of interest exists for the authors.

References

[1]. Rajashekara K. History of electric vehicles in general motors. IEEE Transactions on Industry Applications 1994; 30: 897–904.
[2]. Dekoster DR, Morrow KP, Schaub DA, Hubler NF. Impact of electric vehicles on select air pollution: a comprehensive model. IEEE Transactions on Power Systems 1995; 10:1383–1388.
[3]. Chen CC. An overview of electric vehicle technology. Proceedings of the IEEE 1993; 81(9):1201–1213. 4. Magetto G. Electric vehicle technology: a worldwide perspective. IEE Colloquium on Electric Vehicles—A Technology Road map for the Future (Digest No. 1998/262), 1998, pp. 1/1–110.
[4]. Magetto G. Electric vehicle technology: a worldwide perspective. IEE Colloquium on Electric Vehicles—A Technology Road map for the Future (Digest No. 1998/262), 1998, pp. 1/1–110.
[5]. Young WR Jr. Electric vehicles of yesterday carry us into tomorrow. South con 94 Conference Record, 1994, pp. 14–16.
[6]. Ellers C. Key to saving midtown USA, mass transit and electric vehicles. IEEE Technical Applications Conference and Workshops, Northcon 95, 1995, pp. 406–410.
[7]. Chang L. Recent developments of electric vehicles and their propulsion systems. IEEE Aerospace and Electronics Systems Magazine 1993; 8(12):3–6.
[8]. Ellers CW. Electric transportation: the challenge is yours. Northcon 94 Conference Record, 1994, pp. 331–334.
[9]. Brusagline G. Traction motors for electrically propelled vehicle. Rio Grande Energia 1993; 10:39–46.
[10]. Shimizu H, Harada J, Bland C, Kawakami K, Can L. Advanced concepts in electric vehicle design. IEEE Transactions on Industrial Electronics 1997; 44(1):14–18.
[11]. Naunin D. Electric motors in electric vehicles—a challenge for designers of modern drive systems. International Conference on PEMC, Budapest, Hungary, 1996, Vol. 3, pp. 1–5.

[12]. Shimizu H, Harada J, Bland C. The role of optimized vehicle design and power semiconductor devices to improve the performance of an electric vehicle. Proceedings of the 7th International Symposium on Power Semiconductors Devices and ICs, ISPSD'95, 1995, pp. 8–12.

[13]. Plunkett AB, Plette DL. Inverter-induction motor drive for transit cars. IEEE Transactions on Industry Applications 1977; 13:26–37.

[14]. Wall S. Vector control: a practical approach to electric vehicles. IEE Colloquium on Vector Control and Direct Torque Control of Induction Motors, 1995, pp. 5/1–5/7.

[15]. West JGW. DC, induction, reluctance and PM motors for electric vehicles. IEE Colloquium on Motors and Drives for Battery Powered Propulsion, 1993, pp. 1/1–111.

[16]. Chang L. Comparison of AC drives for electric vehicles—a report on experts opinion survey. IEEE AES Systems Magazine 1994; 9:7–11.

[17] Ramarathnam R, Desai BG. Optimization of poly-phase induction motor design: a nonlinear programming approach. IEEE Transactions on Power Apparatus and Systems 1971; 90:570–578.

[18] Ringlee RJ, Wollenberg BF. Overview of optimization methods. IEEE Tutorial Course: Application of Optimization Methods in Power Systems, 1976, pp. 5–188.

[19] Faiz J, Sharifian MBB. Comparison of two optimization techniques for the design of a three-phase induction motor using three different objective functions. European Transactions on Electrical Power 1995; 5(3):199–205.

[20] Faiz J, Sharifian MBB. Trend of optimization in optimum design of a three phase squirrel-cage induction motor using three different objective functions. IE(I) Journal, India 1997; 77:194–201.

[21] Faiz J, Sharifian MBB. Optimum design of a three phase squirrel-cage induction motor based on efficiency maximization. International Journal of Computers and Electrical Engineering 1995; 21(5):367–373.

[22] Zhang Z, Profumo F, Tenchoni A. Improved design for electric vehicle induction motor using an optimization procedure. IEE Proceedings on Electric Power Applications 1996; 143(6):410–416.

[23]. Pavithran KN, Parimelagan R, Sridhara Rao G, Holtz J. Optimum design of an induction motor for operation with current source inverters. IEE Proceedings, Part B 1987; 134(1):1–8.

[24]. Kim MK, Lee CG, Jung HK. Multi objective optimal design of three-phase induction motor using improved evolution strategy. IEEE Transactions on Magnetics 1998; 34(5):2980–2983.

[25]. Cho DH, Jung HK. Induction motor design for electric vehicle using a niching genetic algorithm. International Conference IEMD'99, Electric Machines and Drives, 1999, pp. 290–292.

[26]. Chen S, Nian Yeh S. Optimal efficiency analysis of induction motors fed by variable-voltage and variable-frequency source. IEEE Transactions on Energy Conversion 1992; 7(3):537–543.

[27]. Faiz J, Ghaneei M, Keyhani A, Proca AB. Optimum design of induction motors for electric vehicles. Electric Machines and Power Systems 2000; 28:1177–1194